2.2 INFRARED PHOTOMETRY AND SPECTROPHOTOMETRY OF TITAN

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Introduction

I would like to begin this discussion of radiometric measurements of Titan with a brief historical review. Since the discovery by Kuiper (1944) of CH_4 bands in the spectrum of this satellite, it has been known that Titan possesses an atmosphere, but following the discussions by Kuiper (1944, 1952), it has been assumed until recently that this atmosphere is very tenuous, with a surface pressure of only a few millibars. Such an atmosphere, as we know from the example of Mars, has only relatively minor effects on the surface temperature, at least in the hemisphere facing the Sun. Thus, it was expected that the mean temperature on the day side of Titan would be approximately that of a hemisphere in equilibrium with the insolation. At Titan's distance from the Sun, the maximum such temperature, corresponding to a blackbody facing the Sun, is 127°K. For an object with the bolometric Bond albedo of Titan, which is, according to Younkin (1973), equal to 0.27, the maximum equilibrium subsolar temperature is 116°K. The corresponding disk-averaged infrared brightness temperature would be about 0.92 times this, or 107°K. These temperatures are a few degrees lower than those that would have been computed a few years ago, primarily as a result of the higher bolometric albedo adopted here; the first authors to measure Titan's radiometric temperature in fact expected to find $110 \leq T \leq 115$°K (Low 1965; Allen and Murdock 1971; Morrison et al. 1972).

Recent observations in a number of areas have changed these expectations and have increased the significance of radiometric measurements of Titan. Most influential has been the work of Trafton (1972a, b), who discovered spectral evidence for H_2 on Titan and presented an important reanalysis of Kuiper's CH_4 observations as well as of his own. The result of this work was to suggest that the surface pressure on Titan is substantially higher, of the order of 0.1 atm. At the same time, polarimetric studies by Veverka (1973) and Zellner (1973), as well as several discussions of the low ultraviolet albedo of this satellite, showed that the atmosphere of Titan contains optically thick clouds and raised the possibility that an extensive and spectroscopically unobserved atmosphere extends to great depths below the cloud layer. An atmosphere of this magnitude might be expected to moderate variations of surface temperature so that the infrared brightness temperature of Titan would approach that of an isothermal object of its albedo and distance from the Sun, which is $T_B \simeq 84$°K.

Recent Radiometric Measurements

With this background, we now turn to the infrared observations, which have provided many surprises during the past 3 years. The first observers to note the anomalously high infrared brightness temperature of Titan were Allen and Murdock (1971), who obtained a temperature of 125 ± 2°K in a band from 10 to 14 μm (nominally 12.4 μm). Since they had expected a maximum brightness temperature of ∿115°K, Allen and Murdock concluded that there was likely to be a greenhouse effect on Titan that increased the observed 12.4-micron flux by a factor of about 2 over the equilibrium level. An earlier brightness temperature of 132 ± 5°K in the 8- to 14-micron band published without comment by Low (1965) was consistent with this suggestion.

The actual magnitude of the change in brightness temperature with wavelength, and hence of the postulated greenhouse effect, became apparent with the publication of additional observations in the infrared. Morrison et al. (1972), observing in a broad band from 16 to 28 μm (nominally 20 μm) found a temperature of 93 ± 2°K, almost as low as the equilibrium temperature for an isothermal satellite. They further documented the range of observed temperatures by quoting unpublished observations by Gillett and Forrest that yielded a disk temperature of 134 ± 2°K at 11 μm and 144 ± 3°K at 8.4 μm. They assumed that the temperature in the atmosphere increases with depth and concluded that the only abundant gas that could provide the indicated great opacity in the 20-micron band together with an opacity decreasing from 12 to 8 μm is H_2 at sufficient pressure to induce translational-rotational transitions. Further, since the bulk of the radiation from such a cool body is at wavelengths between about 15 and 50 μm, they noted that this large opacity in the 20-micron band would result naturally in a greenhouse effect. They therefore argued for a massive hydrogen atmosphere with surface pressure of hundreds of millibars and surface temperatures $\geq$150°K (see also Cruikshank and Morrison 1972). At the same time, calculations by Sagan and Mullen (Sagan 1973) indicated that a pure hydrogen greenhouse on Titan is capable of generating surface temperatures higher than 200°K. These arguments for a massive greenhouse effect have been developed extensively by Pollack (1973) and Sagan (1973) and have encouraged public interest in Titan as a possible abode of life.

A great improvement in the spectral resolution of radiometric measurements has now been achieved by Gillett et al. (1973), who have observed Titan at 8 wavelengths between 8 and 13 μm with a cooled filter-wheel spectrometer having a resolution $\Delta\lambda/\lambda \simeq 0.015$. These narrow-band data, together with several broad-band measurements in the 8-13 μm band, reveal substantial structure in the thermal spectrum, suggestive of line emission. Such structure was not predicted by the greenhouse models (Pollack 1973), but it is consistent with the hot atmosphere model recently proposed by Danielson et al. (1973) as an alternative to the greenhouse models.

One additional infrared measurement of Titan has been made, at 4.9 μm by Joyce et al. (1973). The main constituents suggested for the atmosphere of Titan -- CH_4, NH_3, H_2, and N_2 -- have no absorption bands at this wavelength, so that, aside from possible cloud opacity, a temperature at 4.9 μm might be expected to be characteristic of that near the surface of the satellite. Joyce et al. did not detect 4.9-micron radiation from Titan, but set an upper limit of 190°K. Their observation also restricts the 4.9-micron albedo of Titan to a value of less than 0.5.

All of these observed temperatures are summarized in Table 2-1, categorized as narrow-band and broad-band measurements.

Interpretations

The temperatures shown in Table 2-1 clearly show the large amount of information contained in the infrared observations, information that can be used to distinguish among models. Pollack and Danielson discuss these observations in detail relative to their respective models. I will simply make a few qualitative remarks here about the observations. The most striking feature of these data is the increase in temperature from 20 μm to 8 μm. This

Table 2-1a. Titan Narrow-Band Measurements (Gillett *et al*. 1973)

λ (μm)	T_b (°K)
8.0	158 ± 4
9.0	130 ± 6
10.0	124 ± 3
11.0	123 ± 3
12.0	139 ± 2
12.5	129 ± 2
13.0	128 ± 2

Table 2-1b. Titan Broad-Band Measurements

λ (μm)	Δλ (μm)	T_b (°K)	AUTHORS
4.9	0.8	$\lesssim$190	Joyce *et al*. (1973)
8.4	0.8	146 ± 5	Gillett *et al*. (1973)
10.0	5.0	132 ± 5	Low (1965)
11.0	2.0	134 ± 2	Gillett *et al*. (1973)
12.0	2.0	132 ± 1	Gillett *et al*. (1973)
12.4	4.0	125 ± 2	Allen & Murdock (1971)
20.0	7.0	93 ± 2	Morrison *et al*. (1972)

trend can be understood in terms of either of two very different temperature regimes. The first assumes, perhaps influenced by our experience with Venus and the Jovian planets, that the temperature increases with depth. In this case, the 20-micron temperature corresponds to a level high in the atmosphere, and the shorter-wavelength values to lower levels. Then the opacity must be much greater in the 20-micron band, and one is led naturally to pressure-induced H_2 absorption, a high surface pressure, and a large greenhouse effect. The second model, as suggested by Danielson et al. (1973), assumes that there is a temperature inversion in the atmosphere. In that case, one seeks opacity sources in the 10-micron band, where the hot atmosphere is radiating, while the 20-micron temperature is more likely that of the surface. Such a model does not require either high temperatures or high pressures at the surface of Titan.

Perhaps the most straightforward way to distinguish between these models would be to measure the surface temperature from microwave observations, where the opacity of even a massive atmosphere and clouds is expected to be very small. Such observations have been attempted recently by Briggs and Drake at Cornell with the NRAO interferometer at a wavelength of 3.75 cm. I have been told by Briggs that they have not succeeded in separating the flux density of Titan from the noise and from the much larger flux density of Saturn. Much of the difficulty, as it turns out, is due to poor ephemerides of Titan. It is rather ironic that we are prevented from measuring the surface temperature of Titan only by an inadequate knowledge of its orbit. However, I feel that this effort to observe Titan at microwave frequencies is a very promising line of research, and that it may well provide us with the best means to confirm or refute the greenhouse models in the next year or two.

Another highly promising avenue for research lies in obtaining improved spectrophotometry in the 8- to 14-micron band and in the 17- to 28-micron band. The means now exist to obtain an excellent spectrum from 8 to 14 μm with a resolution of ∿100, and it is probable that in another year it will be possible to achieve a resolution of ∿20 in the 20-micron band. In the 20-micron band, variations of brightness temperature with wavelength due to variations in the opacity of H_2 and CH_4 are predicted by Pollack's (1973) model, but not by Danielson et al. (1973). At the shorter wavelengths also, these two models predict different spectra.

I would like to note here that, no matter what the model, Titan must emit most of its thermal radiation between 15 and 50 μm and (barring an internal heat source), the brightness temperature over this spectral region must average about 84°K, the effective temperature. Thus, I would expect no really big surprises from, for instance, a broad-band measurement at 35 μm. In the 10-micron region, in contrast, only a small fraction of the total thermal energy is emitted, even at brightness temperatures of 150°K. As a consequence, these temperatures are not constrained to be near the effective temperature of Titan, and their wavelength variations can yield valuable information on the temperature structure of the atmosphere.

Summary

In summary, the wide variation in infrared brightness temperature of Titan has, together with the spectroscopic and polarimetric studies, been largely responsible for the great interest in Titan. The original explanation of these

temperatures was in terms of a greenhouse effect, but that interpretation is now being challenged. Further radiometric observations, both in the infrared and at microwave frequencies, appear to provide the best prospects for distinguishing among competing models within the next year or two.

Pollack: I believe I can give some further input on the prospects for additional observations. Gillett is planning to make much more extensive spectrophotometric measurements in the 8- to 13-micron region, and I agree that could help eliminate some of the ambiguities between Danielson and myself. In addition, I think it is very important to search for structure due to pressure-induced bands at longer wavelengths. In that regard, Houck and I are hoping to make use of the NASA C-141 airborne telescope to take a look in the 16- to 60-micron region.

Sagan: A few days ago I talked to Briggs and Drake about their microwave observations and asked them specifically if they could set an upper limit now to the flux density of Titan. I was told they could certainly exclude brightness temperatures of 300°K or higher, but that without a refined ephemeris, they were not sure how much lower they would be able to go.

I would also like to ask if there are any plans for high altitude observations in the 5- to 8-micron region, from aircraft, balloons, or perhaps spacecraft? It is just terribly exciting, this increase in temperature as the wavelength gets shorter and shorter, and it certainly would be interesting to get beyond the atmospheric cut-off at 8 μm.

Morrison: I don't know of any plans. Since Titan is faint and is so close to Saturn, a substantial-sized telescope and very good pointing will be required. Perhaps something could be done from the C-141 in that wavelength range. But we should remember that, even if the brightness temperature is going up, the actual infrared flux densities are dropping very fast as one gets to wavelengths short of 8 μm.

Danielson: I would think that shorter than 8 μm you would principally be examining the CH_4 in the Titan atmosphere. You would learn something about the temperature structure in the upper atmosphere, but I don't think you would be learning anything more fundamental than that.